

# ENHANCED OCEANIC SITUATIONAL AWARENESS FOR THE NORTH ATLANTIC CORRIDOR

Bryan Welch & Israel Greenfeld  
National Aeronautics and Space Administration  
Glenn Research Center  
Cleveland, Ohio 44135  
March, 2004

## ABSTRACT

*Air traffic control (ATC) mandated, aircraft separations over the oceans, impose a limitation on traffic capacity for a given corridor. The separations result from a lack of acceptable situational awareness over oceans where radar position updates are not available. This study considers the use of Automatic Dependent Surveillance (ADS) data transmitted over a commercial satellite communications system as an approach to provide ATC with the needed situational awareness and thusly allow for reduced aircraft separations. Traffic loading from a specific day are used as a benchmark against which to compare several approaches for coordinating data transmissions from the aircraft to the satellites.*

## 1 INTRODUCTION

Current procedures mandate that North Atlantic oceanic air traffic maintain 60 Nautical Miles (NMI) separations [1]. On the other hand, over Continental United States (CONUS) regions, Federal Aviation Administration (FAA) requires a 5 NMI separation. The difference in separation requirements is a direct result of the lack of surveillance radar coverage. Regularly derived position information from radar allows ATC to regularly monitor aircraft positions and react quickly to any changes. The very lack of surveillance radar over oceanic regions means that ATC does not have current position information, and therefore, must maintain much stricter separation requirements.

In the CONUS case where radar coverage is nearly ubiquitous, ATC radar data is automatically received at the regional control centers. Aircraft have little if any requirement to communicate nominal position information to ATC. Over the oceans, ATC must use High Frequency (HF) radio links to request position updates from each aircraft. HF radio has limitations in clarity and reliability. HF radio does not mitigate the burden on ATC to obtain current position knowledge and therefore, the separation requirements cannot be relaxed.

This study explores the technical aspects of a satellite-based approach to oceanic aircraft surveillance that would provide ATC with more timely and reliable position information. This then may provide the means for reducing the current separation requirements and increasing oceanic corridor capacity. Specifically, by all aircraft in the North Atlantic Corridor transmitting their ADS data to an Aeronautical Mobile Satellite System (AMSS) and the AMSS relaying that data to ATC, then the required surveillance information would be available to support reduced separations. The potential AMSS that is considered in this study is a Low-Earth orbiting (LEO) satellite system, but another AMSS in geostationary orbit can fulfill the role as well. The reason for choosing one particular AMSS is that it provides us needed communication systems data for both the space and air segments.

It is noted that this study merely intends to investigate the broad technical aspects of ADS over satellite; that it is cognizant of but is not applying in this study the numerous, strict procedures imposed on oceanic crossing aircraft, in order to obtain a high level indication of what can be achieved just considering communications.

This is a preprint or reprint of a paper intended for presentation at a conference. Because changes may be made before formal publication, this is made available with the understanding that it will not be cited or reproduced without the permission of the author.



## 2 PRELIMINARY CONSIDERATIONS/CALCULATIONS

### **LEO Satellite Link:**

As an example of a LEO satellite system, the Iridium constellation operates in the L-Band frequency and the link examined uses the Sensor Systems Inc. aircraft mounted antenna, S65-8282-401 [2]. The antenna has a minimum elevation angle of  $8^\circ$  with a gain of 0 dBic. The antenna produces 60 Watts (W) power which corresponds to an average power of 42.43 W. This specific antenna was modeled because it is representative of Iridium aircraft mounted antennas. Other link budget assumptions for the study are as follows:

- 3dB of Additional Losses
- QPSK Modulation [3]
- $1E-9$  BER
- Zenith Distance of 780 km [3]
- Horizon Distance of 2460 km [3]
- Frequency of 1.623 GHz
- Iridium Satellite G/T of -16.315 dB/K
- Burst Data Rate of 50 kbps [3]

The resulting link margins, Table 1, for this case are shown below for both the zenith and horizon distances in order to scope the link margin extremes. The horizon distance represents the worst case scenario when the satellite is at an elevation angle of  $8^\circ$ , at the edge of the satellite footprint in the outermost spot beam cells.

**Table 1: Link Margin Results**

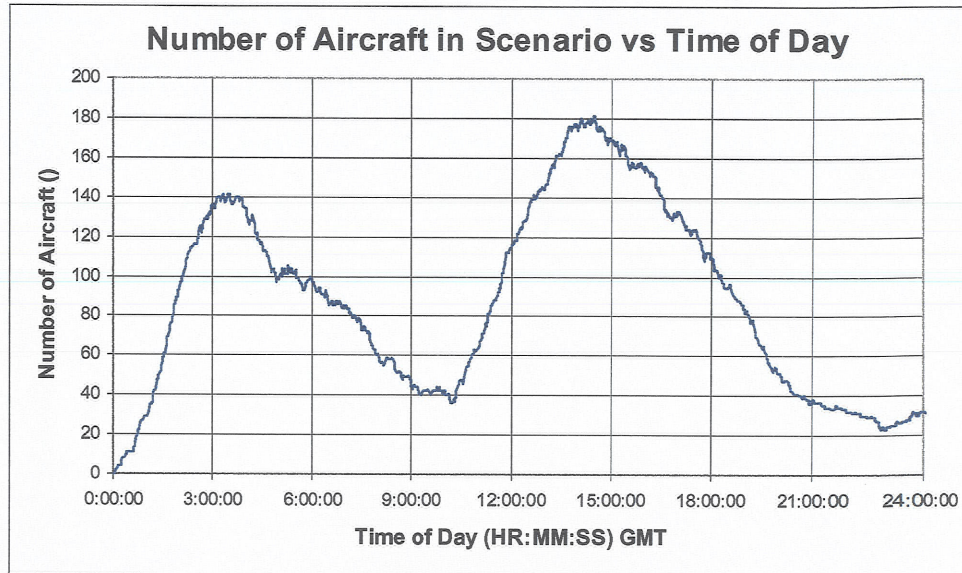
Scenario	Zenith	Horizon
Margin (dB)	11.52	1.55

As shown in Table 1, sufficient margin exists to complete a link assuming level flight for the antenna above  $8^\circ$ .

### **Peak Traffic Baseline:**

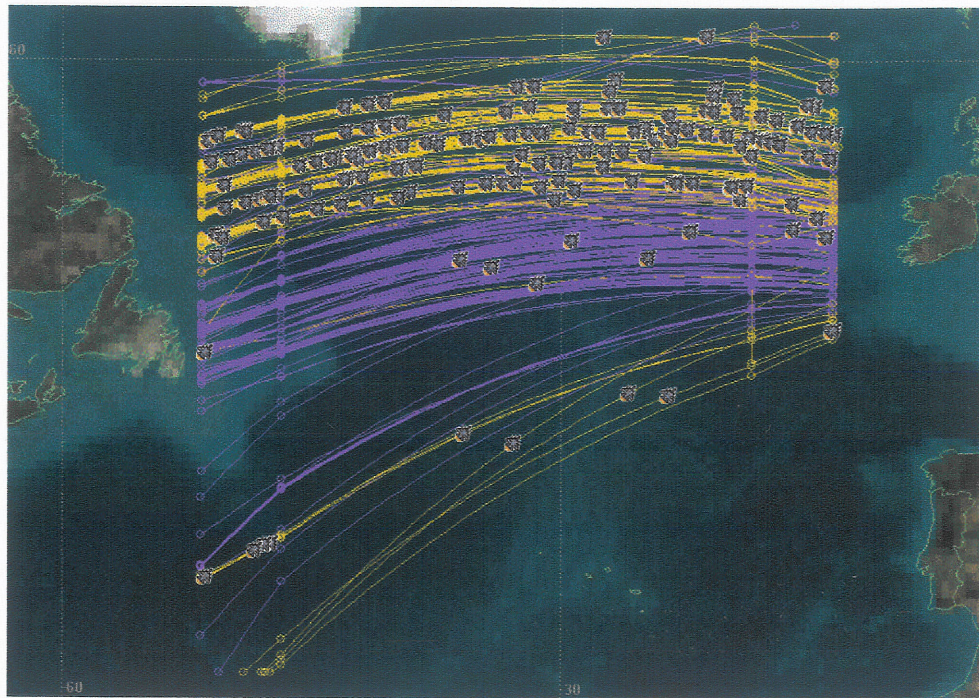
According to the FAA data, July 18, 2001 was the heaviest traffic day in the North Atlantic Corridor that year. Figure 1 shows that the instantaneous, maximum number of aircraft in the corridor was 181. It is noted that the graph is bimodal corresponding to the surge of traffic first going west to east having a peak of 141 aircraft followed by the east to west surge having the 181 aircraft peak. This study uses only the peak traffic density value of 181 aircraft, because that represents the maximum traffic experienced in the North Atlantic Corridor in 2001.





**Figure 1: Number of Aircraft in Scenario**

The peak of 181 aircraft shown in Figure 1 occurs at 14:29 GMT. Figure 2 depicts the aircraft position distribution throughout the North Atlantic Corridor at that specified time. Flight paths shown in gold represent westbound traffic while those in purple represent eastbound traffic.



**Figure 2: Aircraft Coordinates**

### **Corridor Capacity:**

A set of assumptions was used to compute the geometrical maximum number of aircraft in the corridor,  $C_G$ .  $C_G$  is computed in Equation 1, based on the boundaries for the corridor and the aircraft separations.



$$C_G(A_{SEP}) = \left\lceil \frac{1}{2} * \left( \left\lfloor \frac{Alt_{MAX} - Alt_{MIN}}{Alt_{SEP}} \right\rfloor + 1 \right) * \left( \left\lfloor \frac{MIN(d_E, d_W)}{A_{SEP}} \right\rfloor + 1 \right) * \left( \left\lfloor \frac{MIN(d_N, d_S)}{A_{SEP}} \right\rfloor + 1 \right) \right\rceil \quad (\text{Eq. 1}),$$

where:

- $A_{SEP}$  = aircraft separation distance (Nmi)
- $Alt_{MAX}$  = corridor upper altitude = 40,000 ft
- $Alt_{MIN}$  = corridor lower altitude = 38,000 ft
- $Alt_{SEP}$  = required altitude separation = 1000 ft
- $d_E$  = distance of eastern edge of corridor (Nmi) between:
  - North-East boundary (60.0° N, -13.8° E)
  - South-East boundary (50.0° N, -13.8° E)
- $d_W$  = distance of western edge of corridor (Nmi) between:
  - North-West boundary (59.1° N, -51.6° E)
  - South-West boundary (45.2° N, -51.6° E)
- $d_N$  = distance of northern edge of corridor (Nmi) between:
  - North-West boundary (59.1° N, -51.6° E)
  - North-East boundary (60.0° N, -13.8° E)
- $d_S$  = distance of southern edge of corridor (Nmi) between:
  - South-West boundary (45.2° N, -51.6° E)
  - South-East boundary (50.0° N, -13.8° E)

Table 2 lists the maximum number of aircraft, at any given time, that can be geometrically accommodated in the corridor based only on geometry for separations of 60, 45, 30, and 15 Nmi, as calculated by Eq. 1. Notice that by reducing the separation by a factor of 2, the corridor capacity nearly quadruples.

**Table 2: Maximum Geometrical Corridor Capacity**

60 Nmi Separation	314
45 Nmi Separation	546
30 Nmi Separation	1197
15 Nmi Separation	4674

Based just on geometric considerations, even the currently mandated 60 Nmi separation can accommodate more traffic than the peak traffic density of 181 aircraft. The value of 181 aircraft represents the peak instantaneous load for the busiest one-day traffic period, in 2001.

#### **System Refresh Period:**

The maximum system refresh period is the upper limit of the amount of time between position information transmissions to ATC. The term “system refresh period” refers to the amount of time that is required for all of the aircraft in the corridor to transmit their messages one time. For aircraft separation reductions to occur safely, all aircraft in the corridor must transmit their position information within the maximum system refresh period. System refresh period depends on the following [3] [4] [5]:

- Required Navigation Performance (RNP) to aircraft separation ratio
- Latency (delay from transmission to reception) of position message from aircraft to ATC
- Latency of warning message from ATC to aircraft
- Pilot and aircraft response delay from warning message reception at aircraft to aircraft separation stabilization



- Average aircraft speed
- Speed deviation between aircraft
- Standard deviation for Global Positioning System (GPS) reported position
- Aircraft are not flying on the same path in opposite directions
- Aircraft will not arbitrarily change altitudes

Assuming that all the aircraft maintain constant altitude, only latitudinal and longitudinal deviations are an issue. However, the period in between message transmissions represents a time when actual position of planes is uncertain. Therefore, by insisting that the separations remain larger than the sum of the distance two aircraft close in on each other and the RNP distances of the two aircraft during the system refresh period, when their positions are uncertain, the possibility of aircraft getting too close to one another during that time is minimized.

Equation 2, modified from work in [4], calculates the maximum system refresh period, which will be utilized later to determine the corridor capacity due to communications requirements.

$$T_{MAX}(A_{SEP}, \Delta) = \frac{A_{SEP} - 4RNP - 4\sigma_{GPS}}{|\Delta v_{Aircraft}|} - T_{MLatency} - T_{WLatency} - T_{RDelay} - \frac{1}{2} T_{MAX}(A_{SEP}, \Delta) \quad (\text{Eq. 2})$$

The term on the right hand side of Equation 2 of one half of the system refresh period ( $T_{MAX}(A_{SEP}, \Delta)$ ) corresponds to the difference in time due to consecutively situated aircraft transmitting their position reports at time increments of half of the system refresh period. Equation 2 is solved for the system refresh period in Equation 3.

$$T_{MAX}(A_{SEP}, \Delta) = \frac{2}{3} * \left( \frac{A_{SEP} - 4RNP - 4\sigma_{GPS}}{|\Delta v_{Aircraft}|} - T_{MLatency} - T_{WLatency} - T_{RDelay} \right) \quad (\text{Eq. 3})$$

$A_{SEP}$  represents the aircraft separation distance. This study considers  $A_{SEP}$  values of 60, 45, 30, or 15 NMi. RNP is the allowable position error from the planned flight path. The RNP to separation ratio is assumed to have a linear relationship, specifically,  $RNP = k * A_{SEP}$ , where  $k$  is the ratio between RNP and  $A_{SEP}$ . Historical data [5] [6] suggest a value of  $k = 1/6$ . Two historical examples and the projected  $k$  values for the remaining three separations are as follows:

$A_{SEP}$	RNP	k
120 NMi Separation	20 NMi	1/6
60 NMi Separation	10 NMi	1/6
45 NMi Separation	7.5 NMi	1/6
30 NMi Separation	5 NMi	1/6
15 NMi Separation	2.5 NMi	1/6

Other parameters in Equation 3 are:

- $\sigma_{GPS} = 60$  meter standard deviation for GPS
- $\Delta v_{Aircraft} = \frac{11.026 \text{ NMi/min}}{mach} * v_{avg} * \Delta = \text{relative aircraft to aircraft speed deviation in NMi/min}$ 
  - $v_{avg}$  = average aircraft speed of 0.84 Mach
  - $\Delta$  = percent speed deviation between aircraft of 5 or 10 %
- $T_{MLatency} = 1$  minute latency of position message from aircraft to ATC



- $T_{WLatency} = 2$  minute latency of warning message from ATC to aircraft
- $T_{RDelay} = 1$  minute delay of pilot and aircraft response from warning message reception at aircraft to aircraft separation stabilization

Note that the  $\Delta$  parameter helps track aircraft flying at different speeds. The values of 5 and 10% were chosen as reasonable differences between different size aircraft.

It should be noted that due to the values of the message and warning time latencies and response delay ( $T_{MLatency}$ ,  $T_{WLatency}$ , and  $T_{RDelay}$ ), it is possible for the maximum system refresh period to become a negative value. Since this is not allowed, the acceptable range for the maximum system refresh period is all real numbers greater than zero.

Figure 3 illustrates the physical spacing between aircraft that is assumed in Eq. 3. In this figure, the box that surrounds each aircraft represents the containment region of the aircraft. This represents a box of area of 4RNP by 4RNP with the aircraft in the center. The aircraft will have a distance of 2RNP, i.e.  $2\sigma$  deviation from planned flight path, to a box edge. A  $2\sigma$  deviation means that the aircraft should remain on its pre-determined route 95% of the time. The standard deviation for the GPS coordinates of the aircraft,  $\sigma_{GPS}$ , also needs to be considered. The dimensions shown in this figure are not to scale but rather are notional. The figure also shows velocity vectors from which the speed deviation value is derived.

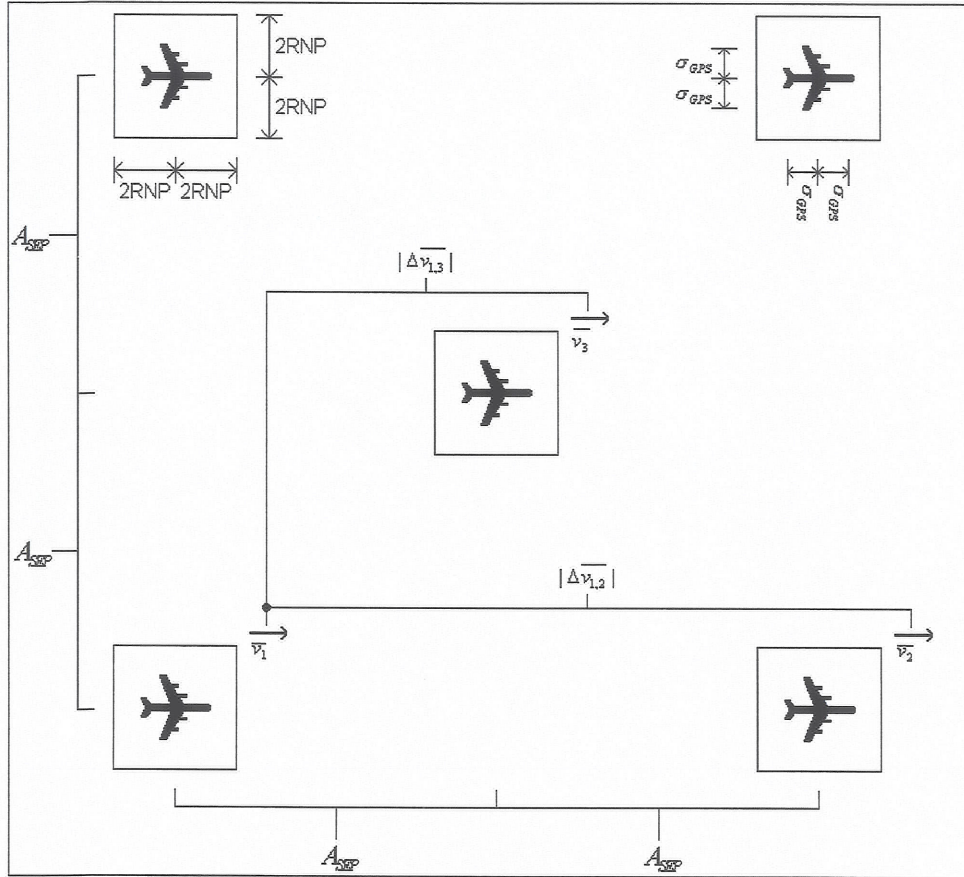
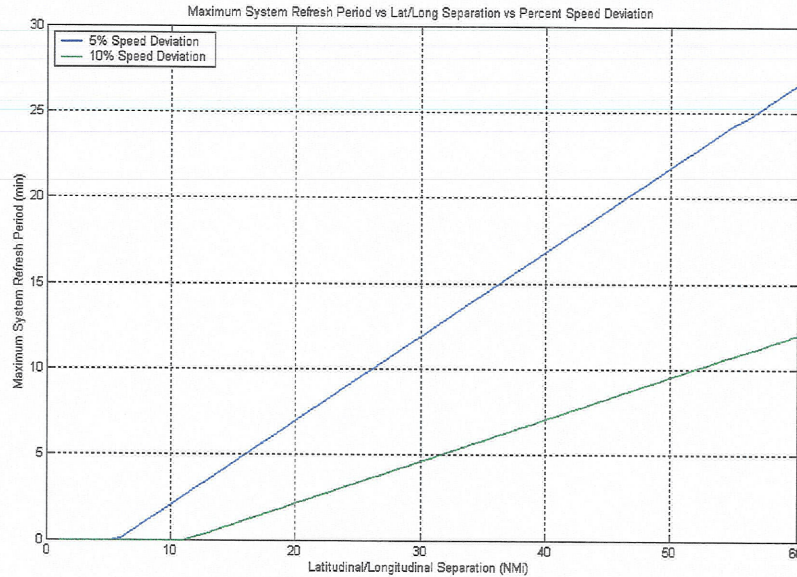


Figure 3: **Example of Aircraft Spacing**

Figure 4 plots the maximum system refresh period,  $T_{MAX}(A_{SEP}, \Delta)$ , for the two speed deviation percentages over the separation distance range of 1 to 60 NMi.  $\Delta v_{Aircraft}$  and  $\Delta$  need to be considered to take into account that



aircraft travel at different speeds. This results in continuous change in relative aircraft separations. Percent speed deviation and aircraft separation determine required system refresh period. Table 3 shows the maximum system refresh period for the four latitudinal/longitudinal separations of interest versus the two speed deviations of 5 and 10%.



**Figure 4: Maximum System Refresh Period**

**Table 3: Maximum System Refresh Period (minutes)**

Separation (Nmi)	5% Deviation	10% Deviation
60 Nmi Separation	26.7	12.0
45 Nmi Separation	19.3	8.3
30 Nmi Separation	11.9	4.6
15 Nmi Separation	4.5	0.9

### 3 Transmission Methods

The following are two methods that were created for the system of aircraft to transmit their GPS derived position for ADS messages. Each method consists of the message transmission description, a system refresh period for the peak traffic of 181 aircraft, and the resulting maximum number of aircraft sustained in the corridor for the maximum system refresh period. The two methods are:

- Method 1 – Single Aircraft Transmission at a Time
- Method 2 – Maximum Aircraft Transmission at a Time

Each method will utilize some, if not most, of the following transmission scheme variables. These variables correspond to the Iridium system [3] [7] [8] and the ADS message format used for the analysis.

- $T_{WAIT}$  = 1 second inter-transmission waiting time between different aircraft transmissions
- $T_{INIT}$  = 20 second initialization time to connect with Iridium (95% probability) [7]
- $M_{CELL}$  = 48 spot beam cells per Iridium satellite (hereafter simply referred to as cell) [3]
- $M_{FCH}$  = 20 frequency channels per Iridium cell [3]
- $M_{TCHF}$  = 4 TDMA channels per frequency channel [3]



- $\%U_{CH} = 81.25\%$  utilization of Iridium channels (not all Iridium channels are full duplex data compatible; therefore less than 100%) [8]
- $R_D =$  System data rate of 2.4 kbps [3]
- $T_{FRAME} =$  Iridium TDMA frame time of 90 milliseconds [3]
- No loss/re-establishment of link occurs during a transmission
- $L_{ADS} =$  ADS message size of 80 bytes including coding [9]

Three values for the inter-transmission waiting time were used in the study (0.33, 0.5, 1.0 second), as this is an uncertain factor, in this paper, only a value of 1 second was reported. Given that the initialization process takes 20 seconds to complete (95% probability) and that 65 active communication channels exist within one cell, the minimum value for the inter-transmission waiting time is just under 0.33 seconds. This means that if a delay of 0.33 seconds is added between transmissions between different aircraft, then up to 65 aircraft in a single cell can be in the process of initializing without conflict for initialization (95% probability).

ADS messages contain the full content of aircraft identification, latitude, longitude, altitude, time stamp, velocity, and future intent. The ADS message modeled is a generic message of size 80 bytes [9]. This message size includes additional coding to help aid in error prevention in the transmission process.

#### Method 1:

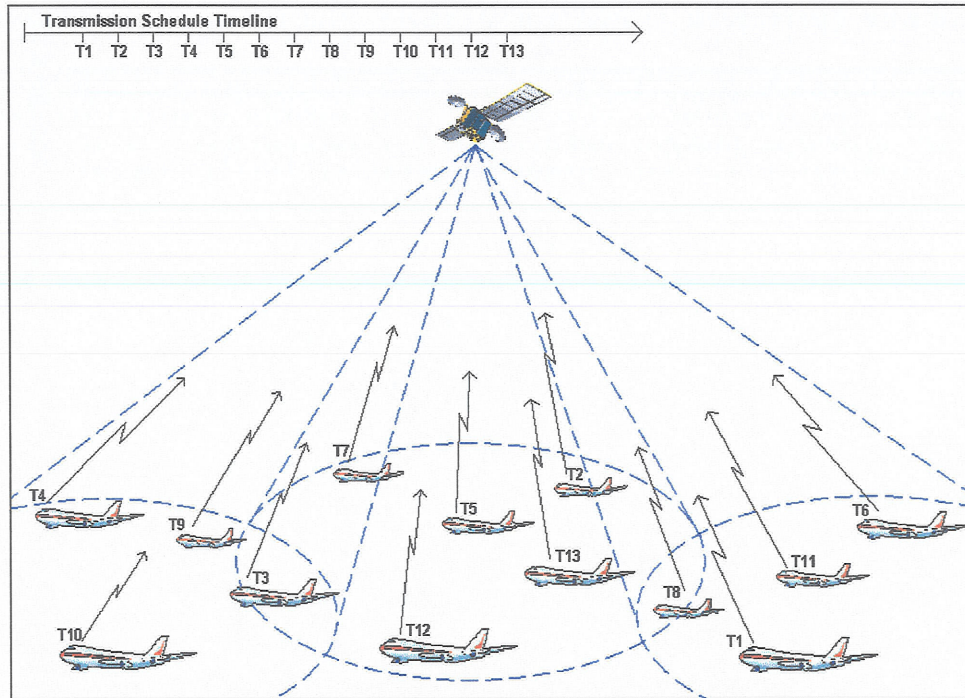
In the single aircraft transmission at a time method, two possibilities were considered. In the first case, the single transmitting aircraft is sending only its own position information. In the second case, the single transmitting aircraft is sending its own plus some of its neighbors' position information.

#### Case 1:

In the first case of Method 1, a single aircraft will transmit its own position information, while others prepare to transmit theirs by initializing their transmitters with the LEO satellite system. An inter-transmission waiting time of one second must elapse before another aircraft in the corridor can transmit. After the completion of the first aircraft's transmission, one of the aircraft which has not transmitted during the current refresh period will initialize with the LEO satellite system. Aircraft will begin to initialize their transmitters 20 seconds prior to their scheduled transmission. The initialization time is not a factor in the calculations because while aircraft  $n+1$  up to aircraft  $n+20$  are initializing, aircraft  $n$  is transmitting so initialization does not contribute a delay to actual operations. This process will continue until all aircraft in the corridor transmit their position information during each system refresh period.

Figure 5 shows an example diagram for Case 1. Note that each aircraft in the corridor has its unique transmission time assignment, represented by  $\{T1, T2, T3, \dots\}$ . These time assignments do not reflect the frequency or time slot that is assigned for the transmission during initialization. It is assumed in the diagram that there are zero conflicts for frequency and time slot assignment.





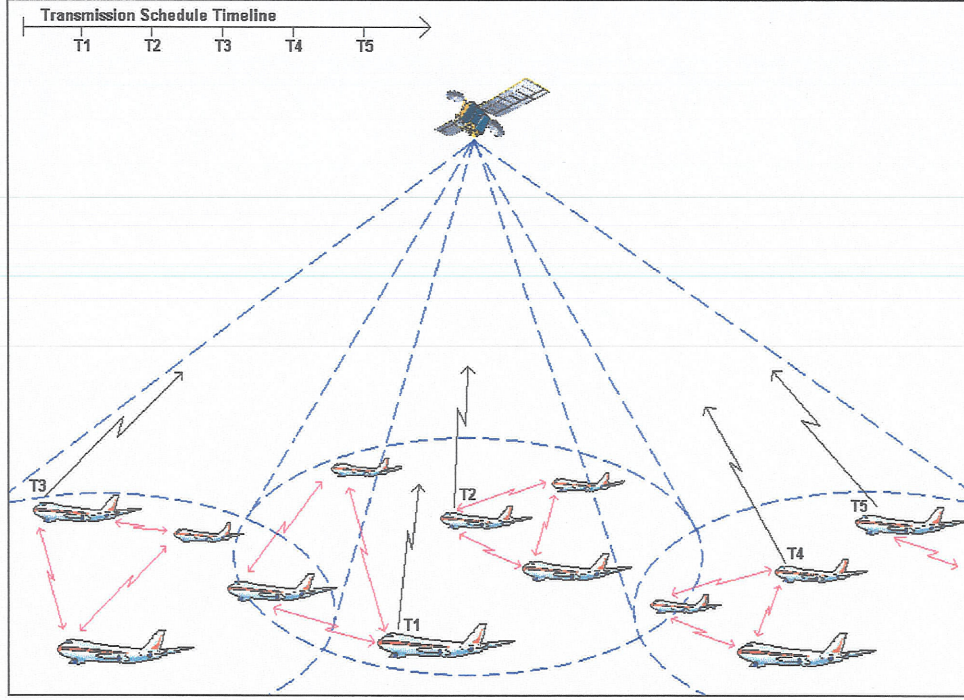
**Figure 5: Example Diagram for Method 1, Case 1**

**Case 2:**

In the second case of Method 1, the transmitting aircraft has knowledge of the position information of neighboring aircraft as well as its own, and those aircraft have knowledge, by use of a status bit, that a particular aircraft will transmit their position information messages. Therefore, those surrounding aircraft will not attempt to initialize and transmit through the LEO satellite system. By insisting that the number of messages that each transmitting aircraft sends be the same, system refresh time can be reduced. The result is fewer transmitting aircraft, fewer messages sent over the LEO satellite system, and a reduction in recurring cost.

Figure 6 shows an example diagram for Case 2. Note that each transmitting aircraft in the corridor has its unique transmission time assignment, represented by  $\{T1, T2, T3, \dots\}$ . These time assignments do not reflect the frequency or time slot that is assigned for the transmission during initialization. It is assumed in the diagram that there are zero conflicts for frequency and time slot assignment. Also, note the transmission links between aircraft. This represents the sharing of position reports on a different link than the LEO satellite system link. The link for sharing these reports is of Automatic Dependent Surveillance – Broadcast (ADS-B).





**Figure 6: Example Diagram for Method 1, Case 2**

The order for which the aircraft will transmit in Method 1 can be accomplished through coordination with ATC. At the time that aircraft are entering the corridor, they are still within HF range. Therefore, using HF communications, ATC can specify an initial transmission time to each aircraft as they enter the corridor, as well as the amount of time between transmissions (system refresh period). Since ATC would be monitoring the flow of traffic over the corridor, it would have knowledge of when aircraft are exiting the corridor, so transmission slots can be reassigned to new aircraft entering the corridor.

For Method 1, the maximum number of possible aircraft in the corridor can be computed based on the geometrical limit in the corridor, LEO satellite data rate, waiting time between aircraft transmissions, and the combined message lengths for the ADS messages. Equation 4 computes the capacity for the communication scheme for Method 1.

$$C_{C1}(A_{SEP}, \Delta, b) = b * \left[ \frac{T_{MAX}(A_{SEP}, \Delta) * 60 \text{ sec/min}}{\left( T_{FRAME} * \left\lceil \frac{b * 8 * L_{ADS}}{R_D * T_{FRAME}} \right\rceil + T_{WAIT} \right)} \right] \quad (\text{Eq. 4}),$$

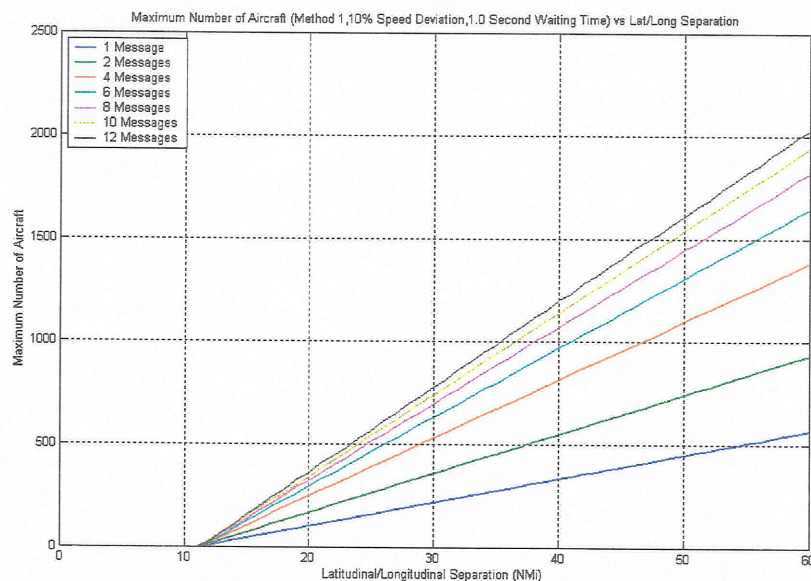
where:

- $b$  = number of messages per transmission
- $T_{MAX}(A_{SEP}, \Delta)$  = maximum system refresh period dependent on  $A_{SEP}$  (separation) and  $\Delta$  (percent speed deviation)
- $L_{ADS}$  = length of ADS message of 80 bytes
- $T_{FRAME}$  = Iridium TDMA frame time of 0.090 seconds
- $R_D$  = System data rate of 2.4 kbps
- $T_{WAIT}$  = 1 second inter-transmission waiting times between different aircraft transmissions



Figure 7 shows the maximum number of aircraft as a function of separation for 10% speed deviation and 1.0 second inter-transmission waiting time. Note that for each case of  $b$ , number of messages per transmission, the resulting graph is a straight line that associates number of aircraft that can be supported at a given separation with a specified maximum system refresh period.

For a given value of  $b$ , number of messages per transmission, as separation increases, the system refresh period also increases. The reason is, as aircraft are further apart, there is a less frequent need for position updates to maintain good separation knowledge (see Figure 4). Figure 7 shows that for a given value of  $b$ , as separation increases, the maximum number of aircraft also increases. As just stated, separation increases relate directly to increases in maximum system refresh period. In turn, increasing maximum system refresh period will directly increase the number of messages that can be sent. Finally, the number of aircraft that can be supported will increase, by a factor of  $b$ , as the number of messages sent increases. Intuitively, as the number of messages per transmission increases, then the time required for a single transmission will increase, which will decrease the number of possible transmissions sent during a given time interval. However, as the number of possible transmissions sent will decrease, the overall number of aircraft that the system can handle will increase due to the larger number of aircraft position reports being sent.



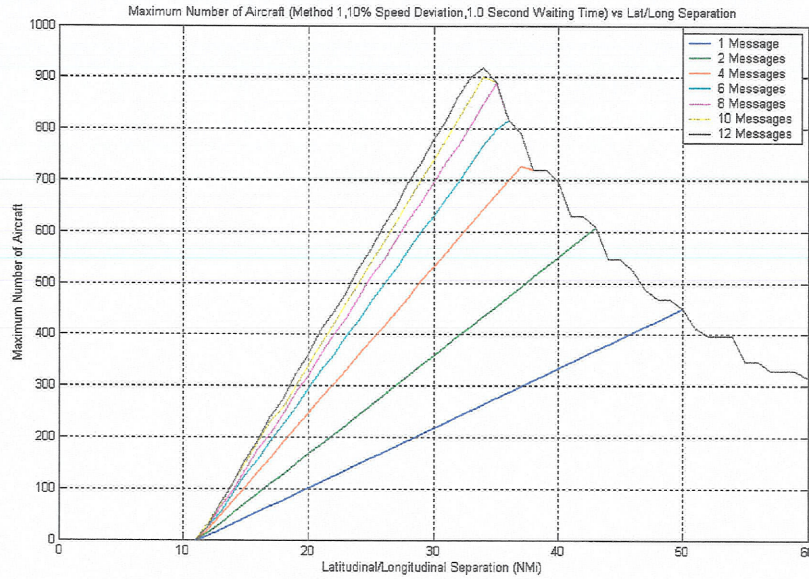
**Figure 7: Maximum Number of Aircraft – Communications Limits**

Equation 5 computes the overall maximum number of aircraft in the corridor as the lower bound between the geometrical capacity and the communication scheme capacity at varying separations.

$$C_1(A_{SEP}, \Delta, b) = \text{MIN}(C_G(A_{SEP}), C_{C1}(A_{SEP}, \Delta, b)) \quad (\text{Eq. 5})$$

Given the maximum system refresh period, the maximum number of aircraft that the corridor can sustain for Method 1 is computed for a speed deviation of 10% of the average speed. The results for 1.0 second inter-transmission waiting times are plotted in Figure 8.





**Figure 8: Maximum Number of Aircraft – Method 1**

Figure 8 shows the combined effects of geometric and communications systems limits. The right hand boundaries observed in Figure 8 represent the geometric limits for maximum possible number of aircraft, as a function of aircraft separation (see Table 2), while the straight lines represent communications limits based on maximum system refresh period, as a function of aircraft separation (see Figure 7).

Table 4 lists the maximum number of aircraft for the four separations versus the number of messages per transmission. Note that in all cases of 15 NMi separation, this method does not meet the peak traffic density. However, for the remaining cases, Method 1 does accommodate the current peak traffic density.

**Table 4: Maximum Number of Aircraft – Method 1**

Messages per Transmission	60 NMi	45 NMi	30 NMi	15 NMi
1	314	392	218	43
2	314	546	358	72
4	314	546	532	104
6	314	546	630	126
8	314	546	696	136
10	314	546	740	150
12	314	546	780	156

From these separations, the best results in terms of maximum number of aircraft in the corridor occur when the separation requirement is 30 NMi with 12 messages per transmission. This is because the 30 NMi separation results in the largest geometric capacity given the system refresh period function decreasing with smaller separations, over the four separations.

#### **Method 2:**

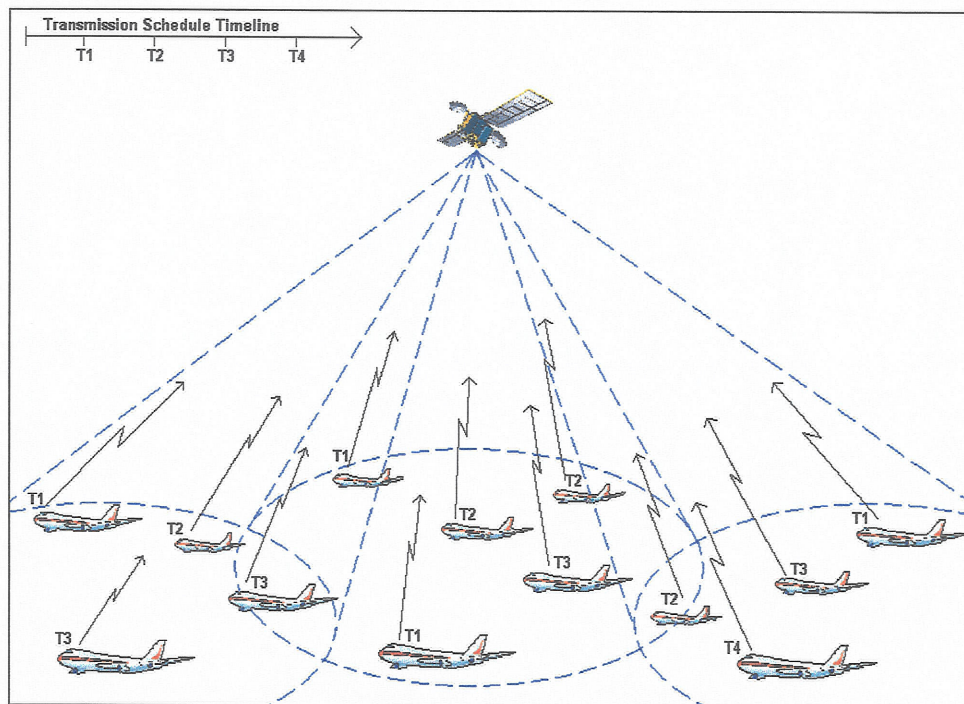
In the maximum aircraft transmission at a time method, two possibilities were again considered. In the first case, transmitting aircraft send only their own position information. In the second case, transmitting aircraft send their own plus information of its neighbors' position information.

#### **Case 1:**



In the first case of Method 2, a maximum number of aircraft in the corridor will transmit their position information. This maximum number of concurrent transmissions is determined from the number of available LEO satellite data transmission channels in a cell. However, as the distribution of aircraft is dynamic over the moving LEO satellite cells, the maximum possible number of concurrent transmissions is the maximum number of active data channels in a single cell. Once the first group of 65 aircraft transmits their position information, a 1 second inter-transmission waiting time separation is elapsed before another group of 65 aircraft begins to initialize and transmit to the LEO satellite system. In this method, the initialization time is a factor because parts of group  $n+1$  might be covered within the same cell(s) as group  $n$ . This cycle will repeat as necessary for all the aircraft in the corridor to transmit their position information during each system refresh period.

Figure 9 shows an example diagram for Case 1. Note that each aircraft in the corridor has a transmission time assignment, represented by  $\{T1, T2, T3, \dots\}$ . These time assignments do not reflect the frequency or time slot that is assigned for the transmission during initialization. It should be noted that several aircraft have the same transmission time assignment  $\{T1, T2, \dots\}$ . For those with the same time assignment, transmissions will take place concurrently. It is assumed in the diagram that there are zero conflicts for frequency and time slot assignment. Thus, if two aircraft are in the same cell and have the same time assignment, then they will be on a different frequency or time slot from each other.



**Figure 9: Example Diagram for Method 2, Case 1**

#### Case 2:

In the second case of Method 2, the transmitting aircraft have knowledge of the position information of surrounding aircraft as well as their own, and those aircraft have knowledge that a set of aircraft will transmit their position information messages. Therefore, those surrounding aircraft will not attempt to initialize and transmit through The LEO satellite system. By insisting that the number of messages that each transmitting aircraft sends be the same, system refresh time can be reduced. The result is fewer transmitting aircraft, fewer messages sent over the LEO satellite system, and a reduction in recurring cost.

Figure 10 shows an example diagram for Case 2. Note that each transmitting aircraft in the corridor has a transmission time assignment, represented by  $\{T1, T2, T3, \dots\}$ . These time assignments do not reflect the frequency or time slot that is assigned for the transmission during initialization. Also, note the transmission links between aircraft. This represents the sharing of position reports on a different link than the LEO satellite system link. The



link for sharing these reports is ADS-B. For those with the same time assignment, transmissions will take place concurrently. Again, it is assumed in the diagram that there are zero conflicts for frequency and time slot assignment. Thus, if two aircraft are in the same cell and have the same time assignment, then they will be on a different frequency or time slot from each other.

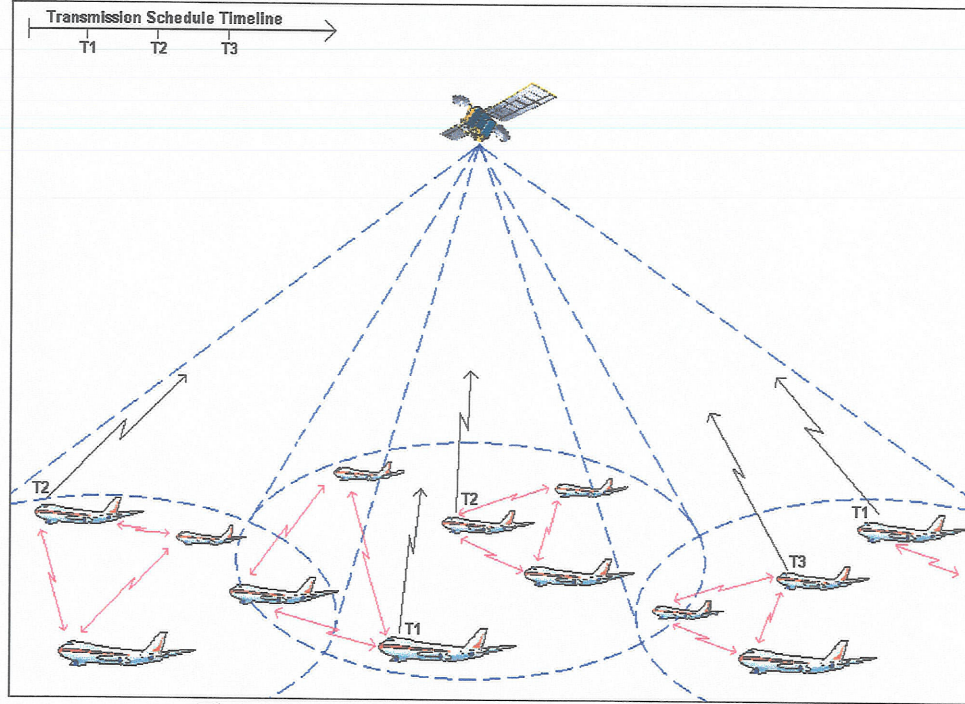


Figure 10: **Example Diagram for Method 2, Case 2**

The order for which the aircraft will transmit in Method 2 can be accomplished through coordination with ATC. At the time that the aircraft are entering the corridor, they are still within HF range. Therefore, using HF communications, ATC can specify and initial transmission time to each aircraft as they enter the corridor, as well as the amount of time between transmissions (system refresh period). Since ATC would be monitoring the flow of traffic over the corridor, it would have knowledge of when aircraft are exiting the corridor, so it can open up those transmission slots for new aircraft upon entering the corridor.

For Method 2, the maximum number of possible aircraft in the corridor can be computed based on the geometrical limit in the corridor, LEO satellite data rate, waiting time between messages, initialization time to the LEO satellite system, combined message lengths for the ADS messages, LEO satellite transmission channels per cell, and LEO satellite transmission channel utilization. Equation 6 computes the capacity for the communication scheme for Method 2.

$$C_{C2}(A_{SEP}, \Delta, b) = b * \left[ \frac{T_{MAX}(A_{SEP}, \Delta) * (60 \text{ sec/min}) * \lfloor M_{FCH} * M_{TCHF} * \%U_{CH} \rfloor}{\left( T_{FRAME} * \left[ \frac{b * 8 * L_{ADS}}{R_D * T_{FRAME}} \right] + T_{WAIT} + T_{INIT} \right)} \right] \quad (\text{Eq. 6}),$$

where:

- $b$  = number of messages per transmission
- $T_{MAX}(A_{SEP}, \Delta)$  = maximum system refresh period dependent on  $A_{SEP}$  (separation) and  $\Delta$  (percent speed deviation)

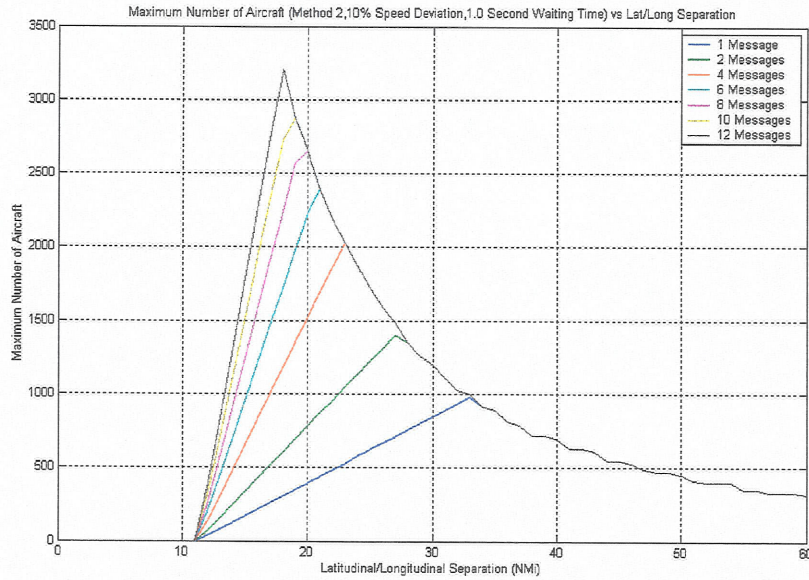


- $L_{ADS}$  = length of ADS message of 80 bytes
- $T_{FRAME}$  = Iridium TDMA frame time of 0.090 seconds
- $R_D$  = System data rate of 2.4 kbps
- $T_{WAIT}$  = 0.33, 0.5, and 1 second inter-transmission waiting times between different aircraft transmissions
- $T_{INIT}$  = 20 second initialization time to connect with Iridium (95% probability)
- $M_{FCH}$  = 20 frequency channels per Iridium cell
- $M_{TCHF}$  = 4 TDMA channels per frequency channel
- $\%U_{CH}$  = 81.25% utilization of Iridium channels (not all Iridium channels are full duplex data compatible; therefore less than 100%)

Equation 7 computes the overall maximum number of aircraft in the corridor as the lower bound between the geometrical capacity and the communication scheme capacity at varying separations.

$$C_2(A_{SEP}, \Delta, b) = \text{MIN}(C_G(A_{SEP}), C_{C2}(A_{SEP}, \Delta, b)) \quad (\text{Eq. 7})$$

Given the maximum system refresh period, the maximum number of aircraft that the corridor can sustain for Method 2 is computed for a speed deviation of 10% of the average speed. The results for 1.0 second inter-transmission waiting time are plotted in Figure 11.



**Figure 11: Maximum Number of Aircraft – Method 2**

Figure 11 shows the combined effects of geometric and communications systems limits. The right hand boundaries observed in Figure 11 represents the geometric limits for maximum possible number of aircraft, as a function of aircraft separation (see Table 2), while the straight lines represent communications limits based on maximum system refresh period, as a function of aircraft separation (see Figure 7).

Table 5 lists the maximum number of aircraft for the four separations versus the number of messages per transmission for the 10% speed deviation. Note that in one situation of 15 NMI separation, this method does not meet the peak traffic density. However, for the remaining spacing and transmission situations, Method 2 does accommodate the current peak traffic density.



**Table 5: Maximum Number of Aircraft – Method 2**

Messages per Transmission	60 NMi	45 NMi	30 NMi	15 NMi
1	314	546	846	169
2	314	546	1197	334
4	314	546	1197	652
6	314	546	1197	954
8	314	546	1197	1248
10	314	546	1197	1520
12	314	546	1197	1788

From these separations, the best results in terms of maximum number of aircraft in the corridor occur when the separation requirement is 15 NMi with 12 messages per transmission. This is because the 15 NMi separation results in the largest geometric capacity given the system refresh period function decreasing with smaller separations, over the four separations.

#### 4 AIRCRAFT LOADING IMPROVEMENT

Having shown two methods for which the system of aircraft can transmit their data to ATC within the maximum allowed system refresh period, a traffic loading improvement measure will be considered.

The measure compares the maximum number of aircraft of the two transmission methods at 10% speed deviation for a single, double, quadruple, and a twelve message per transmission case for each method against the peak traffic density of 181 aircraft. It should be noted that the 10% speed deviation corresponds closely to the deviations resulting from head/tailwinds. A single message per transmission (b=1) represents an aircraft having to know only their own position. Table 6 shows the percent differences between the 181 aircraft and the number of aircraft calculated previously and shown in Table 4 for Method 1 and Table 5 for Method 2. Table 6 is based on Eq. 8, where N represents the number of aircraft that can be placed in the corridor at the specified separations.

$$\%Increase = 100 * \frac{N - 181}{181} \quad (\text{Eq. 8})$$

**Table 6: Absolute Percent Increase in Maximum Aircraft**

b	Lat/Long Separation (NMi)	Method 1	Method 2
		1.0 sec	1.0 sec
1	60 NMi Separation	73	73
	45 NMi Separation	117	202
	30 NMi Separation	20	367
	15 NMi Separation	-76	-7
2	60 NMi Separation	73	73
	45 NMi Separation	202	202
	30 NMi Separation	98	561
	15 NMi Separation	-60	85
4	60 NMi Separation	73	73
	45 NMi Separation	202	202
	30 NMi Separation	194	561
	15 NMi Separation	-43	260
12	60 NMi Separation	73	73
	45 NMi Separation	202	202
	30 NMi Separation	331	561



15 NMi Separation	-14	888
-------------------	-----	-----

Table 6 shows that the largest overall percentage increase in traffic over the peak traffic density is a 888 % increase with the following conditions:

- 15 NMi separation
- Method 2
- 12 messages per transmission

If implementation allows only a single message per transmission, then the largest percentage increase in traffic density is a 367 % increase with the following conditions:

- 30 NMi separation
- Method 2
- 1 message per transmission

## 5 CONCLUSIONS

This study is a high level, theoretical effort to understand and analyze oceanic aircraft traffic loading. Numerous assumptions were made but care was taken to list them all. Given that the assumptions are correct, then the increases in traffic capacity shown in this report are also correct in a technical sense. The results generally show capacity increases when combining reduced aircraft separation requirements with ADS transmissions to ATC. Such capacity increases suggest that introducing ADS data over satellite communications links will accommodate potential traffic growth. It is strongly cautioned that incorporating procedural requirements would greatly change the results.

The study established an analytical methodology to analyze this kind of scenario. Table 2 shows that based only on geometry, the corridor can support 314 aircraft at a separation of 60 NMi. Note that 60 NMi is the current mandated oceanic separation, and is based on a lack of surveillance data. That being so, adding ADS transmissions through an AMSS are of no benefit for 60 NMi separation situations. However, ADS transmissions can be the enablers for reduced separations.

## REFERENCES

- [1] Federal Aviation Administration, "National Airspace System Architecture Version 4.0," <204.108.10.116/nasiHTML/nas-architecture/>, January 1999.
- [2] Sensor Systems Inc., <www.sensorantennas.com/pdf/S65-8282-401.pdf>, May, 1998.
- [3] Fossa, Carl E., Raines, Richard A., Gunsch, Gregg H., Temple, Michael A., "An Overview of the Iridium Low Earth Orbit (LEO) Satellite System," IEEE, 1998.
- [4] Flax, Bennett, "A Minimum Rate of Position Reporting in the Future Oceanic Air Traffic Control System," IEEE Plans '92, March 1992.
- [5] Shakarian, Arek, Haraldsdottir, Aslaug, "Required Total System Performance and Results of a Short Term Conflict Alert Simulation Study," 4<sup>th</sup> US/Europe Air Traffic Management R & D Seminar, Sante Fe, December 2001.
- [6] Aimer, Jeff, "Required Navigation Performance for Improved Flight Operations and Efficient Use of Airspace," <www.boeing.com/commercial/aeromagazine/aero\_12/navigation.pdf>, October 2000.
- [7] Lemme, Peter W., Glenister, Simon M., Miller, Alan W., "Iridium Aeronautical Satellite Communications," IEEE, 1998.



[8] Hubbel, Yvette C., "A Comparison of the IRIDIUM and AMPS Systems," IEEE Network, March/April 1997.

[9] Eurocontrol, "Eurocontrol Standard Document for Surveillance Data Exchange Part 12 Transmission of ADS-B Messages," <[www.eurocontrol.int/asterix/documents/p12ed010.pdf](http://www.eurocontrol.int/asterix/documents/p12ed010.pdf)>, March 2000.